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TITLE: IDENTIFICATION AND REDUCTION OF WAKEFIELD EFFECTS IN THE WIGGLER REGION OF THE LOS ALAMOS FREE-ELECTRON LASER

AUTHOR(S): A. H. Lumpkin, D. W. Feldman, R. W. Warren, W. E. Stein, D. Chan

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

IDENTIFICATION AND REDUCTION OF WAKEFIELD EFFECTS IN THE WIGGLER REGION OF THE LOS ALAMOS FREE-ELECTRON LASER*

A. H. Lumpkin, D. W. Feldman, R. W. Warren,

W. E. Stein, and K. C. D. Chan

Los Alamos National Laboratory

P. O. Box 1663

Los Alamos, New Mexico 87545, USA

ABSTRACT

Improving the performance of the Los Alamos Free-Electron Laser (FEL) in 1988 involved the identification and reduction of wakefield effects generated in the wiggler region. The wakefield effect was dramatically reduced by inserting a smooth metal tube into the wiggler gap, and the FEL performance was concomitantly improved.

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I. INTRODUCTION

An important step in improving the performance of the Los Alamos Free-Electron Laser (FEL) in 1988 involved the identification and reduction of wakefield effects generated in the wiggler region. Prior to implementation of these reductions, we had not seen clearly defined "buckets" in the electron spectra under oscillator lasing conditions as had been observed in the amplifier experiment with the same wiggler [1,2]. By using our diagnostic technique based on a fast *rf* deflector, a spectrometer, and a gated, intensified television camera [3], we were able to demonstrate that the observed increase in "energy spread" at higher peak currents (I >100 A) was actually a longitudinal wakefield effect in the wiggler zone occurring on the submicropulse time scale ($\leq$10 ps). As this effect was shown to occur in the wiggler, we also projected that electron-trapping in the bucket would be affected deleteriously.

II. EXPERIMENTAL CONSIDERATIONS AND BACKGROUND

The Los Alamos FEL is an *rf*-LINAC driven oscillator operating normally at λ ~10μm . For completeness, a layout of this facility is shown in Fig. 1. Two linear accelerator sections that have separate *rf* power sources accelerate the beam to 21 MeV. The 100-μs long macropulse consists of ~2000 micropulses with 46.3 ns separation, 20 ps duration, and 2 to 5 nC of charge. A nonisochronous 60° bend that brings the electron beam onto the FEL resonator axis can also be used as a magnetic buncher to produce micropulse lengths $\leq$10 ps. After the wiggler a slow deflector, an *rf* fast deflector, a quadrupole, and the electron spectrometer provide the potential for time-resolved energy spectra on the macropulse and micropulse time-scales [3,4]. The information from the focal plane is recorded by two gated, intensified television cameras. The fast deflector cavity generates the transverse deflection.

Beamline emittance growth issue had been investigated on our beamline previously and reported at the Williamsburg FEL Conference [5]. At that time emittance growth contributions were assigned to the beamline diameter discontinuities associated with wall current monitors (WCM), bellows, the 60° bend magnet box, and the wiggler area. Figure 2 shows data from our studies in 1986 on wakefield effects which presumably included contributions from all four of the above sources. At that time a simple scaling of energy droop with instantaneous current within the micropulse could qualitatively reproduce the data structure as seen in the left column of Fig. 2. The purpose of this report is to discuss the effects that remained after our campaign to smooth the beamline and which were localized to the wiggler region of our FEL. The twenty pump-out vanes of the wiggler support frame that were created when the wiggler gap was shimmed open to 8.8 mm evidently became wakefield generators. Figure 3 shows a schematic of the wiggler case and the effective step-up, step-down transitions in the beamline geometry that the electron beam would "see".

In Fig. 4 the wake functions of geometries including a step-up and a step-down transition are shown. The wake functions are labeled $\theta 1 + \theta 2$ where $\theta 1$ and $\theta 2$ are the step-up and step-down taper angles respectively. The vertical axis gives the bunch energy spread per ampere and the horizontal axis is referenced to the bunch temporal profile. A more complete discussion of such calculations is given by Chan [6] One would anticipate that this potential would generate an oscillatory structure on the energy vs. time profile of the micropulse.

The modeling of the sub-micropulse energy-time intensity distribution incorporated a number of working assumptions.

1) The distribution of the electrons entering the accelerator is assumed to have a Gaussian time and energy spread whose full width at half maximum intensity equal 30 ps and 0.5%, respectively, at 20 MeV.

2) The energy added to an electron by the accelerator is given by a cosine function with the period of the rf's 1.3 GHz.

3) The effect of the nonisochronous bend is approximated as delaying the electrons by 26 ps per 1% ΔE.

4) In the simple calculation of Fig. 2, an energy depression proportional to the local charge density is added.

5) For the wiggler wakefield measurements, the energy depression added was the oscillatory wake function calculated as in Fig. 4. The amplitude was scaled by the number of discontinuities and the width to the nominal 10-ps pulse length.

6) The electron spectrometer focal plane image with the fast deflector active was simulated by turning on pixels with a probability proportional to the charge density.

A direct comparison to data is presented in the next section.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, only samples from a rather extensive experimental study of the wiggler region wakefield effects will be presented. The second aspect will be representation of some of the observed improvements in FEL performance after we reduced the wakefield effect.

As an initial point of reference, Fig. 5 shows the effect of increased peak current on the observed energy-time distribution. Keep in mind that this hairpin shape is observed on the sub-micropulse time scale. The upper image was obtained at a WCM reading of 1A (~1/2 nC) and the lower image for a WCM reading of 5A-(~2 1/2 nC). The vertical dagger on the left of the hairpin in the lower image is attributed to the wakefields. A graphical analysis of the effect is shown in Fig. 6 where in addition to the ϕ_B value of 74-77° the unloaded ϕ_B = 53° trace is shown. ϕ_B is an arbitrary phase of accelerator B with respect to A, and is varied to produce bunching in the nonisochronous bend. The 2% bar indicates an estimate of the energy depression that the electrons at the top of the hairpin must have incurred to be localized into the vertical dagger pointing downward. In this regime, the 2 nC charge increase, which was a five-fold increase over the initial 1/2 nC per micropulse, resulted in a 1%/100A energy depression at the maximum. The 10-ps pulse duration was assumed. Another test of the interpretation was provided by removing the wiggler case and replacing it with a smooth pipe that matched the beamline diameter. Figure 7 shows focal plane images at even higher currents/charges with a much reduced energy effect. It is noted that these data were taken several weeks after those of Fig. 5.

One of our more graphic examples of the phenomenon is shown in Fig. 8 where the simulation program image on the left is seen to be strikingly similar to the oscillatory experimental image. The energy and time scales are approximately adjusted to be comparable. The simulation energy depression is about .5% per 100A at 186A peak current for 5 nC per pulse. All four vertices (intense image at charge collection points) are seen in both the experiment and the image. As a further test of this interpretation, a smooth tube was placed within the wiggler gap so that the electrons were shielded from the case's discontinuities. The energy depression with the micropulse was reduced by a factor of 2 to 3.

The culmination of these efforts was described previously by Warren, et al. in that the FEL with a wakefield suppressing tube in the wiggler approached near-ideal performance [7]. Besides the improved spectral purity, the trapping of electrons became more efficient. The localization of the trapped electrons more nearly matched calculations. Figure 9 shows that the experimental cavity length detuning curve became very similar to the calculated curve for the uniform wiggler experiment. The suppression of sidebands by detuning the cavity became a demonstrated fact. Shortly after these experiments the high extraction efficiency results from the tapered wiggler with a prebuncher were performed [8]. Figure 10 compares our previous electron beam 2% extraction result from several years ago (upper) to that of 1988 (lower) The extended tail to low energy out to 15% for the lasing condition for the 12% linear taper wiggler was not predicted by calculations without wakefields. However, the expected bucket position at about -7% in energy in the lower figure is as predicted. It is noted that the prebuncher enhanced the trapping in the lower figure in addition to our having reduced the wakefields with the tube inserted in the wiggler gap. The improved agreement between simulations in which wakefields were not included and experiments in which wakefields were reduced is understandable.

IV. SUMMARY AND CONCLUSIONS

We have obtained a good, qualitative, if not quantitative, description of the energy droop within a micropulse caused by wakefields. This was accomplished by using an oscillatory wakefield potential calculated for a step-up, step-down transition in the beamline geometry and a simulation program that combined the distribution of charge in energy and time after the two accelerators, the nonisochronous 60°, and the twenty transitions of the wiggler case (due to pumpout vanes). The simulation program generated an "image" of the two-dimensional energy-time domain created by the fast deflector and spectrometer magnet at the focal plane. The similarity of the experimental image's and the simulated image's oscillatory structure is striking. The wakefield effect was dramatically reduced by inserting a smooth metal tube into the wiggler gap. This tube then shielded the charged-particle beam from the wiggler case discontinuities. More importantly, subsequent FEL operations showed improved spectral purity, more clearly defined cavity length detuning effects, and a better trapping of electrons.

FIGURE CAPTIONS

Fig. 1. The Los Alamos FEL beamline configuration in 1988.

Fig. 2. Wakefield effects observed in 1986 before the beamline discontinuities were reduced.

Fig. 3. Schematic mechanical design of the wiggler case.

Fig. 4. Wake functions calculated for three geometries including the step-up, step-down transition.

Fig. 5. Images from the spectrometer focal plane for different beam currents.

Fig. 6. Graphical analysis of the wakefield's energy depression effect.

Fig. 7. Observed time-resolved energy distribution in the spectrometer when the wiggler was replaced by a smooth pipe.

Fig. 8. Comparison of the observed time-resolved energy distribution with that of the simulation.

Fig. 9. Comparison of experimental and simulated cavity length detuning curves for the uniform wiggler (see Ref. 7).

Fig. 10. Comparison of electron beam spectral evidence for extraction efficiency without and with the wiggler wakefield reducing tube, respectively the upper and lower plots. A prebuncher was also used in the lower data to enhance trapping efficiency (see Ref. 8).

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LOS ALAMOS FEL (1988)

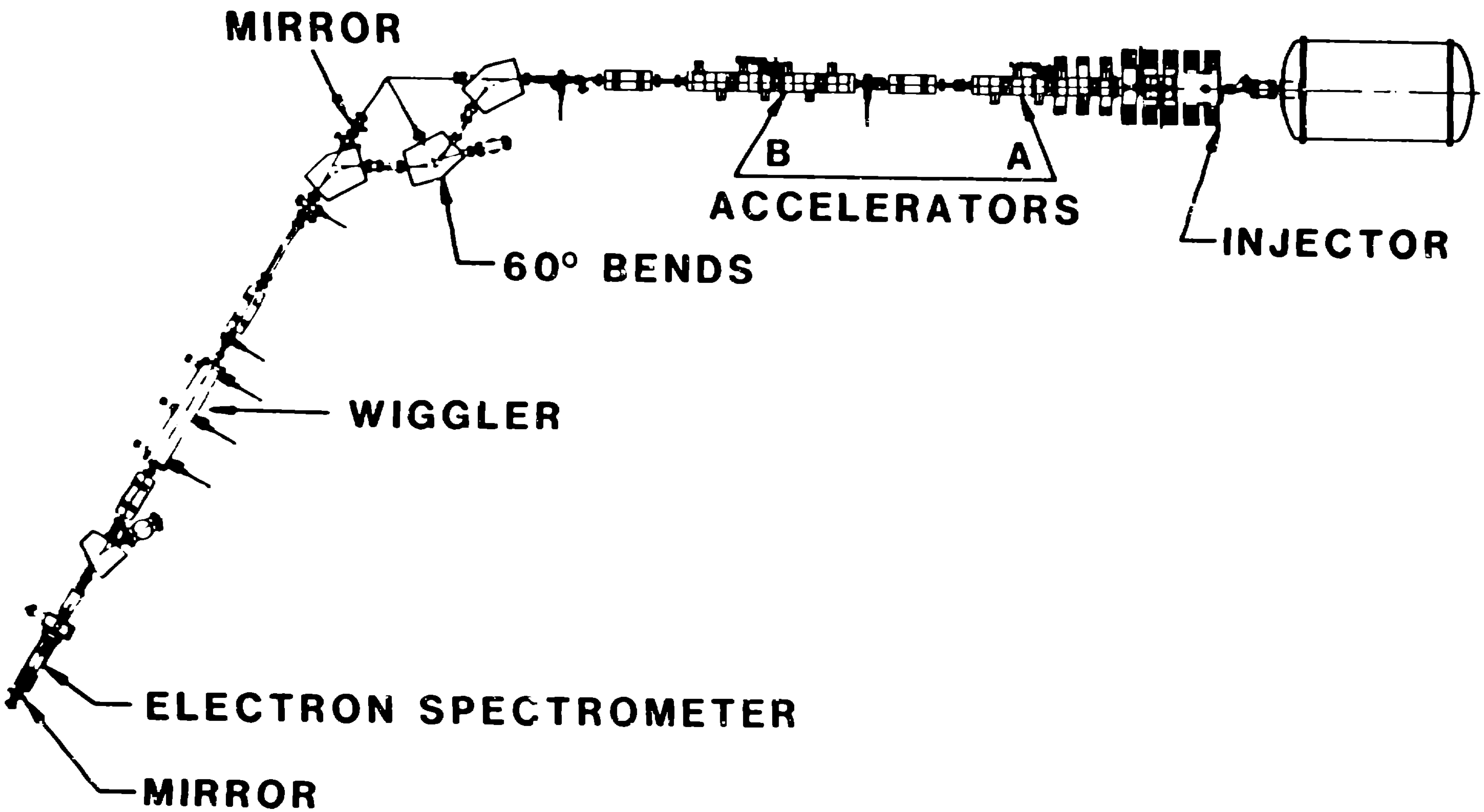


Fig. 1

Wakefield Effects Observed in 1986 Experiments with Deflector/Spectrometer

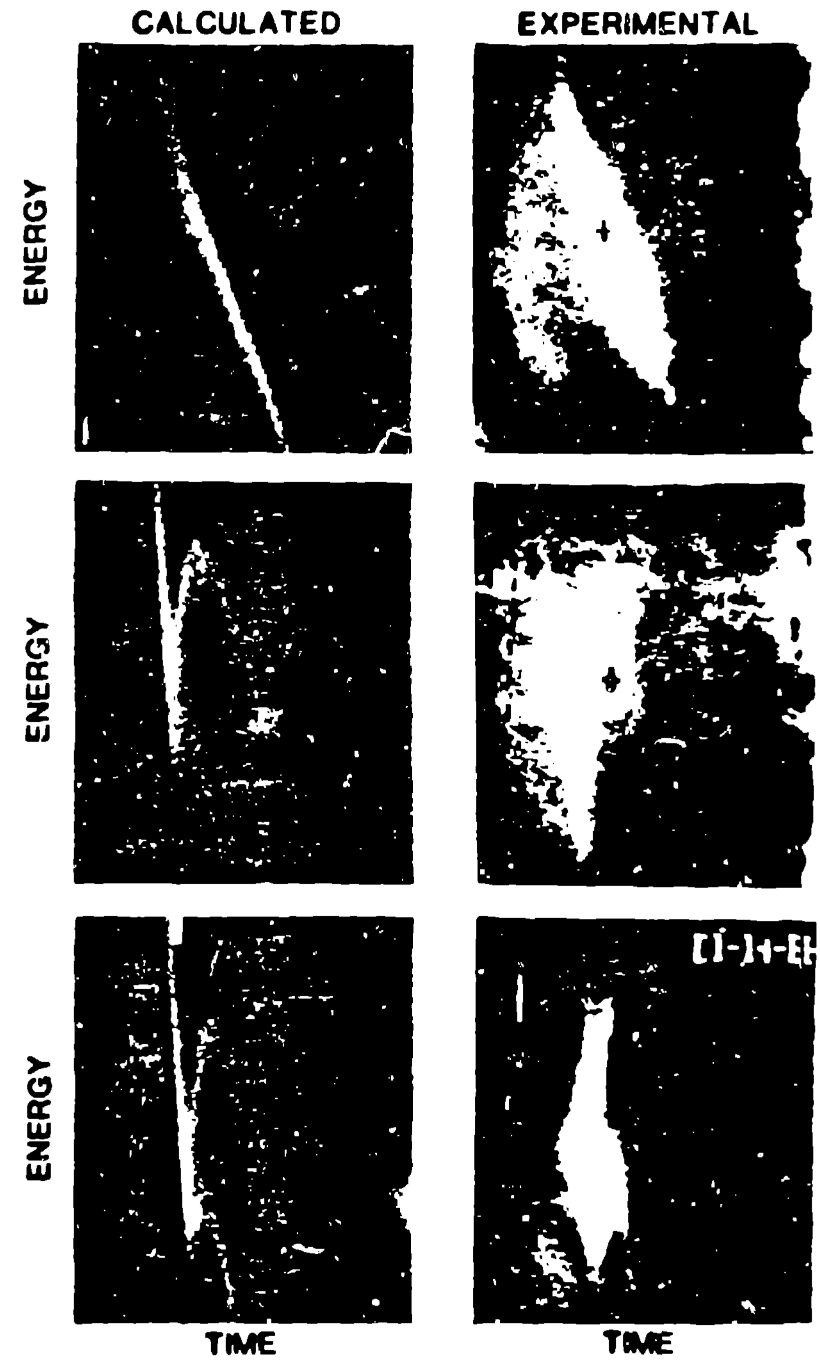


Fig. 2

Wiggler Case Appeared as Series of Beamline Discontinuities to Electron Beam

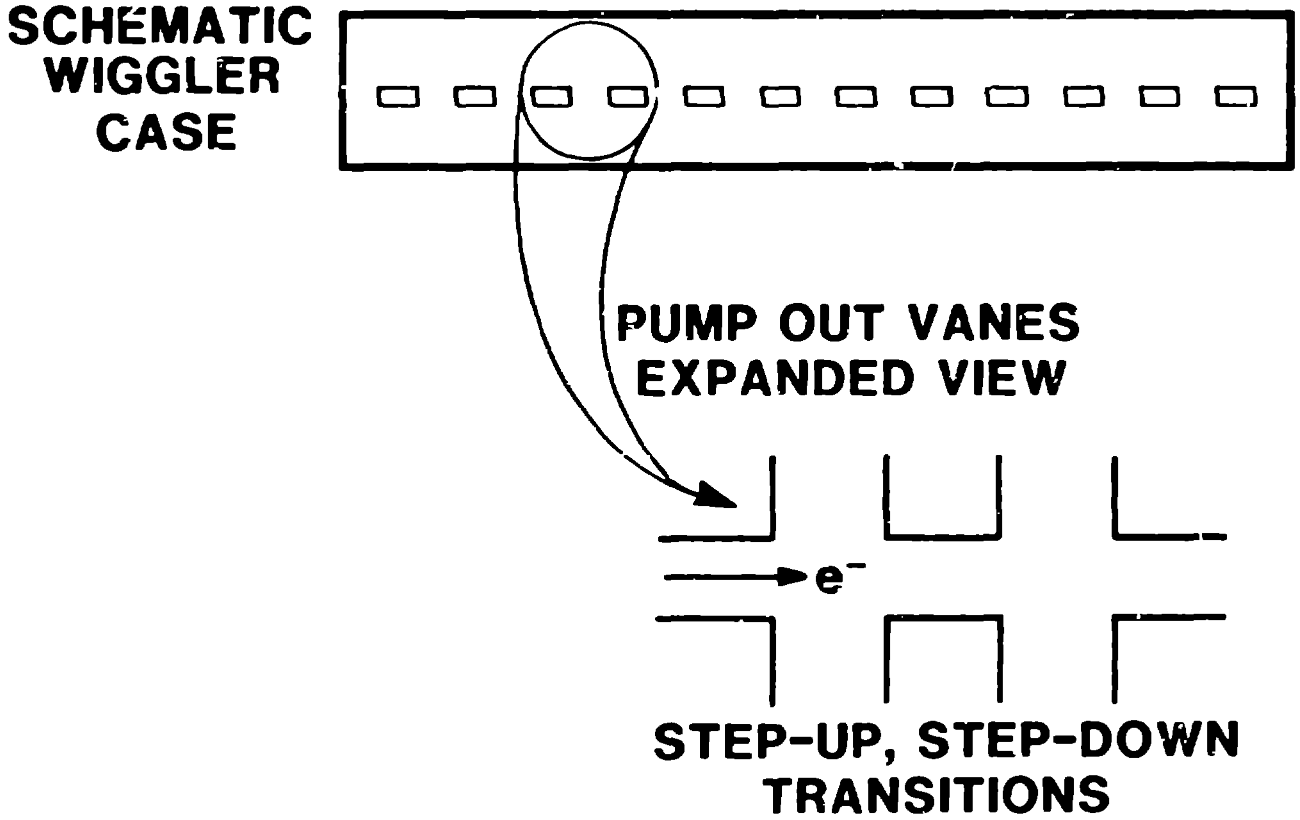


Fig. 3

The wakefunctions of geometries including a step-up and a step-down transition. The wavefunctions are labeled θ1 + θ2 where θ1 and θ2 are the step-up and step-down taper angles respectively

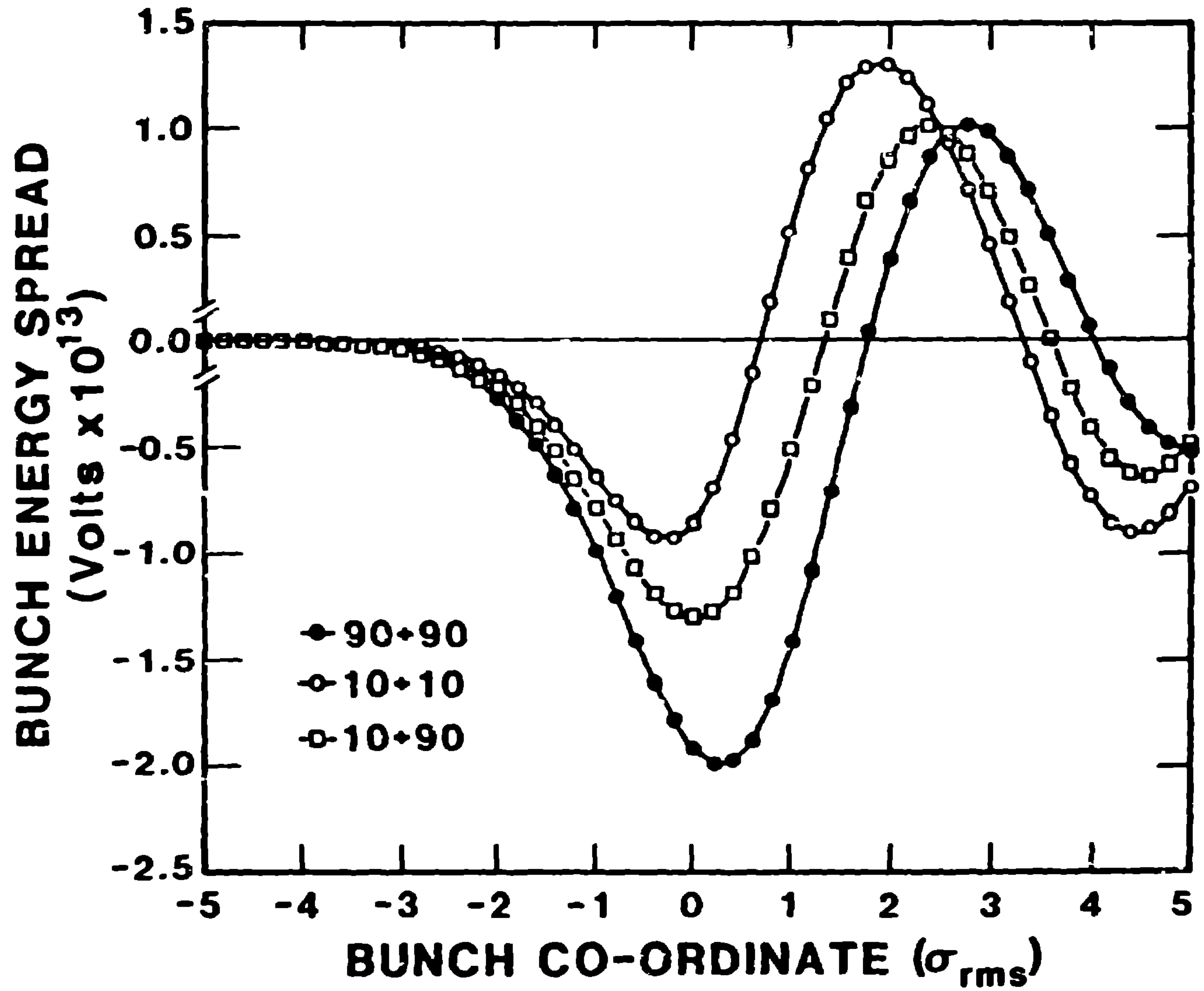
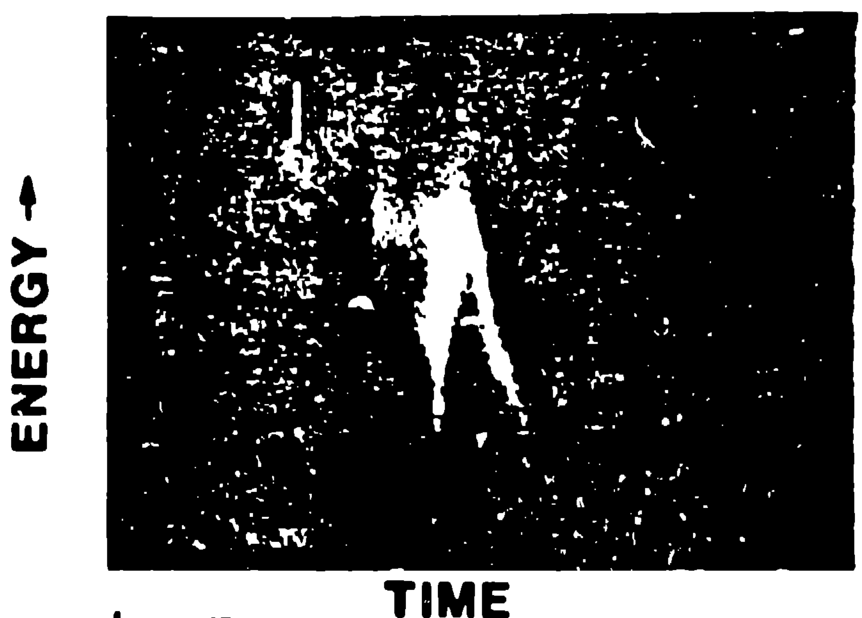


Fig. 4

Wakefield Effects Increase with Peak Current
(10-21-87)

$\phi_B = 74°$

$I_7 = 1A$ S# 10,280



$\phi_B = 74°$

$I_7 = 5A$ S# 12,030

Graphical Overlay of Submicropulse Data Shows Wakefield Effect for Different Charge

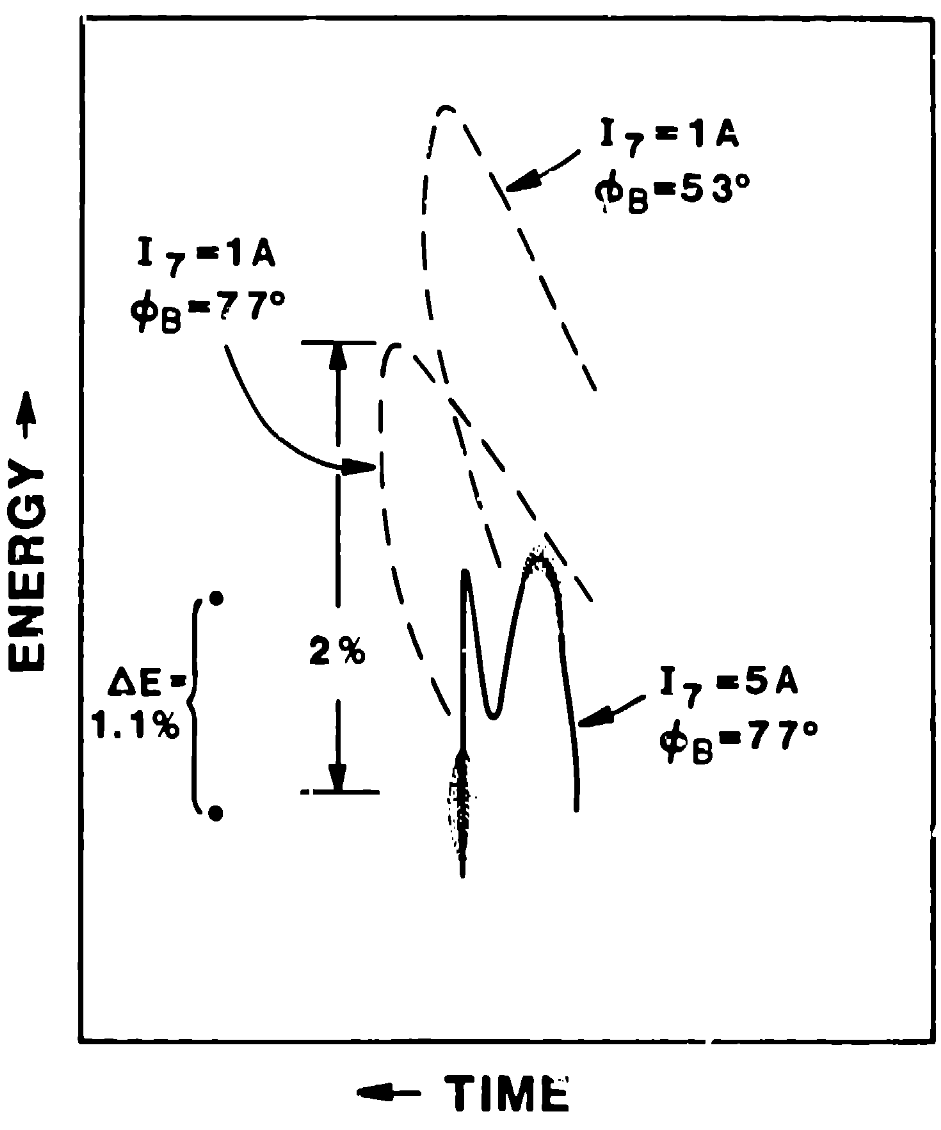
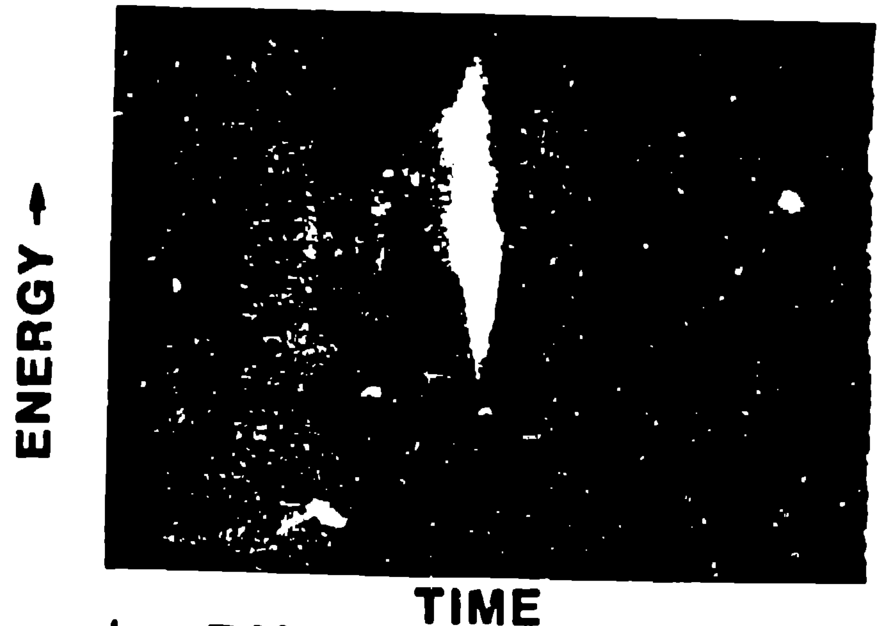
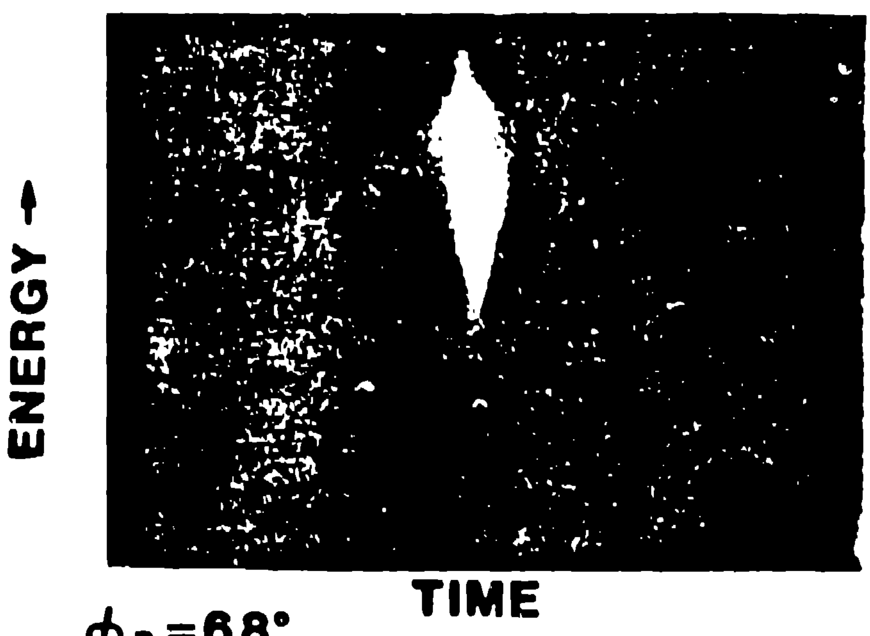


Fig. 6

Smooth Pipe in Place of Wiggler Shows Reduced Energy Effect
(11-19-87)



$\phi_B = 72°$
$I_7 = 8.0A$



$\phi_B = 68°$
$I_7 = 7.8A$

SIMULATION PROGRAM REPRODUCED EXPERIMENT DATA STRUCTURE

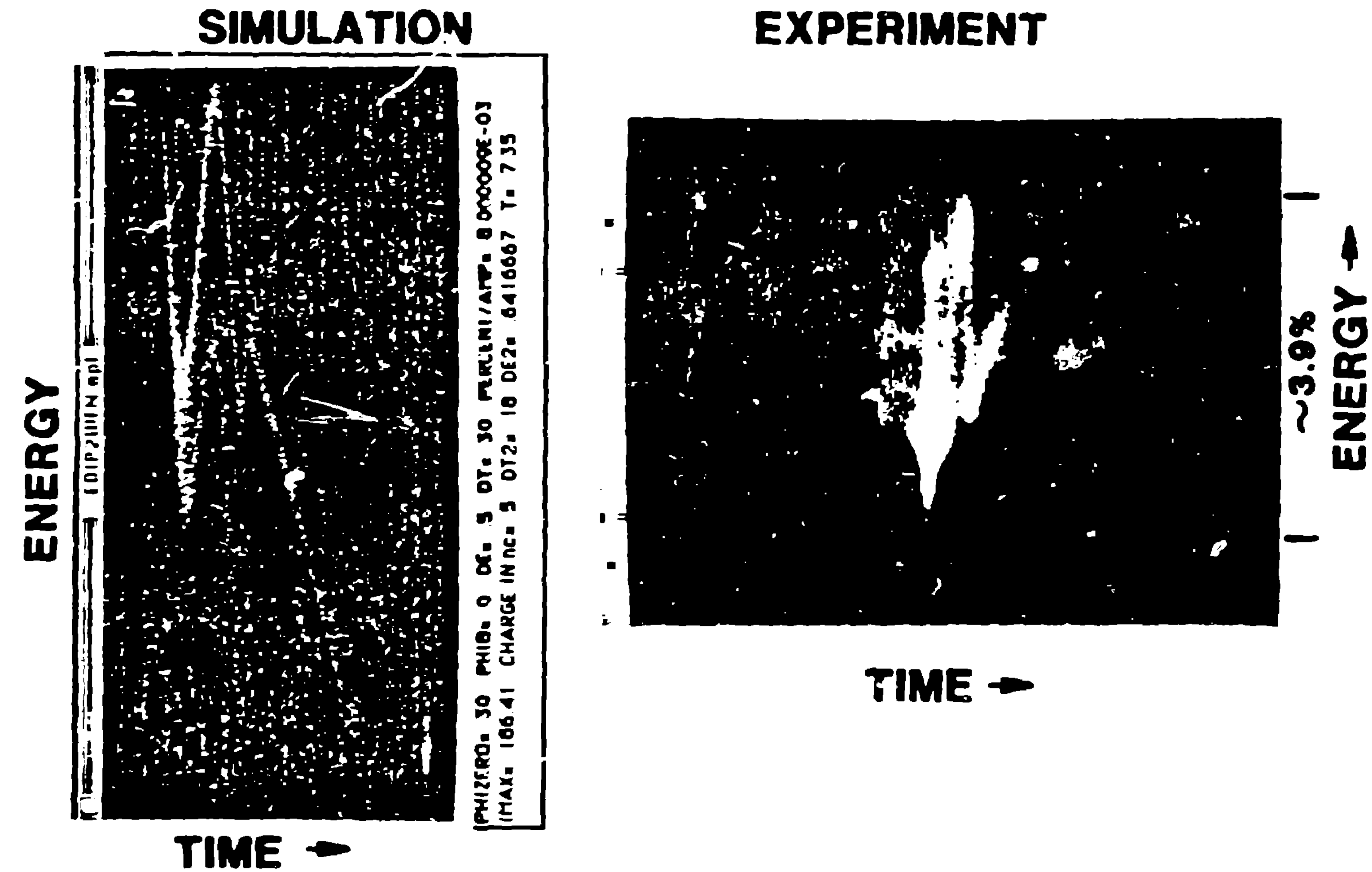


Fig. 8

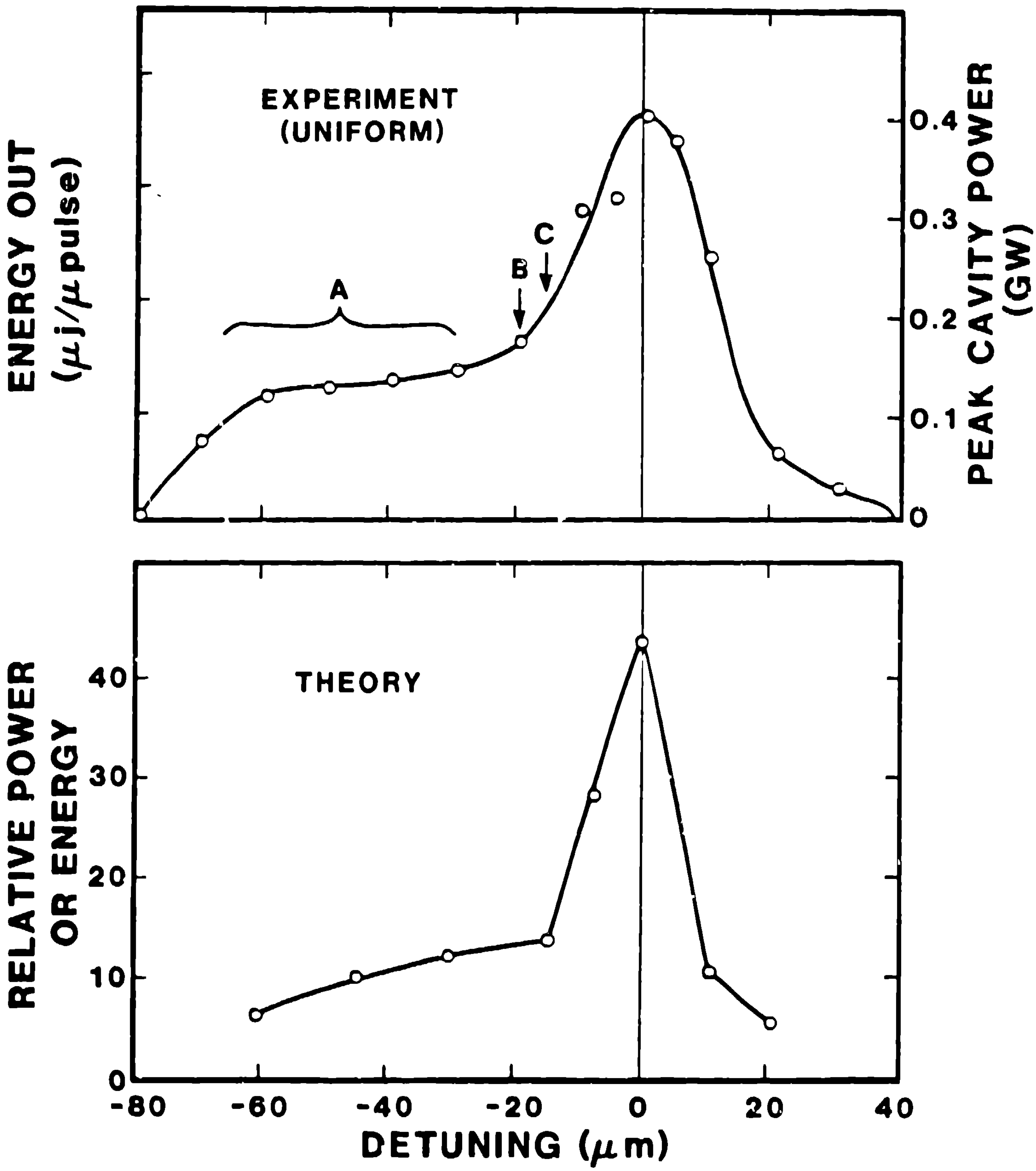
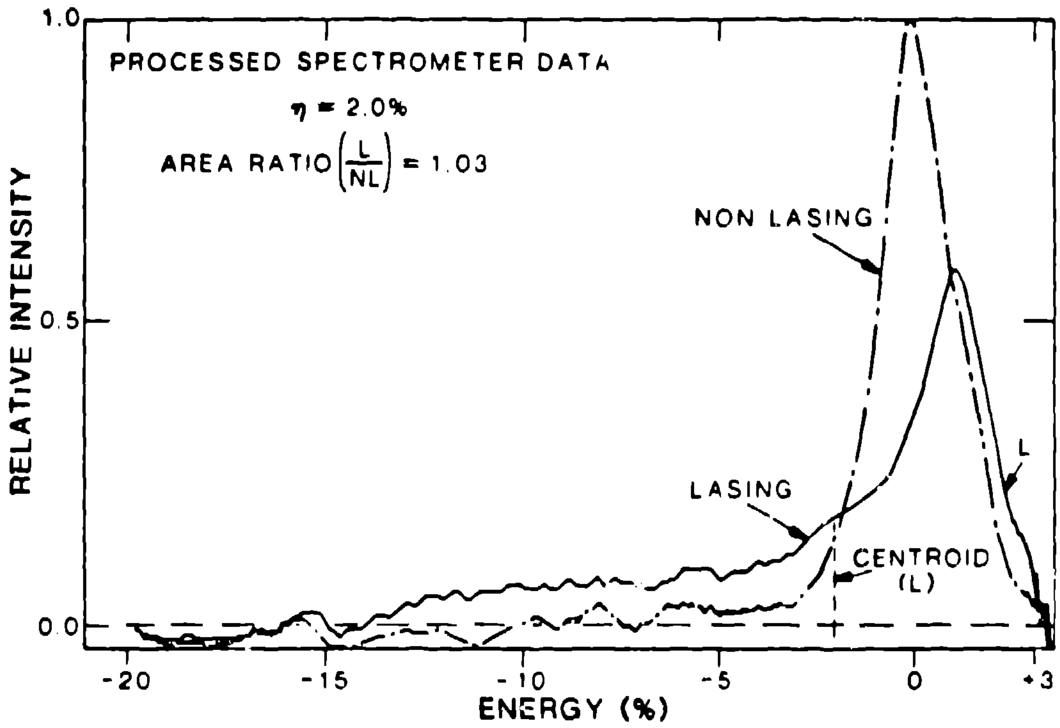

EXPERIMENT
(UNIFORM)
ENERGY OUT
(μj/μpulse)
PEAK CAVITY POWER
(GW)
0.4
0.3
0.2
0.1
0
A
B
C
THEORY
RELATIVE POWER
OR ENERGY
40
30
20
10
0
-80
-60
-40
-20
0
20
40
DETUNING (μm)

Fig. 9

Trapped Electrons Localized in Bucket (Tapered Wiggler Result)



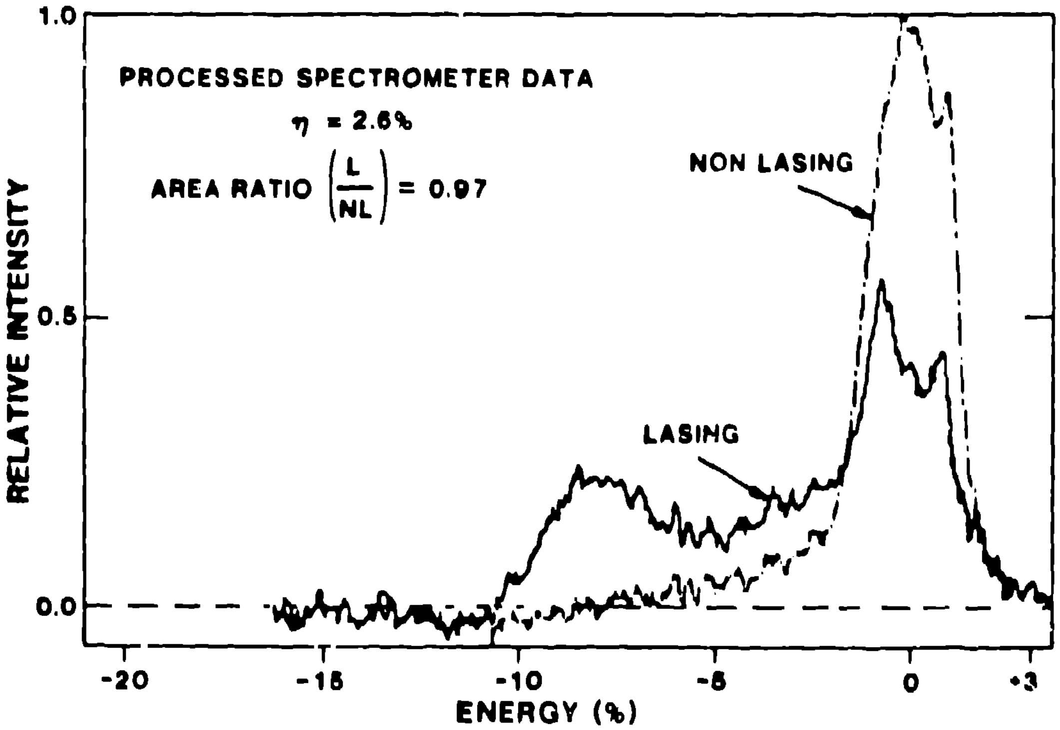


Fig. 10